A DEMONSTRATION PLAN FOR LASER-BEAMED POWER

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ABSTRACT

In a constrained budgetary era under pressure to develop faster, better, and less expensive space projects, efforts to develop laser-beamed power for lunar and propulsion applications must first focus on defining near-term, commercially attractive deliverables that will demonstrate progress toward, and engender support for development of an operational laser-beamed earth-orbital propulsion/lunar power system. A near-term (within three years) laser-beamed power application with commercial promise is satellite rejuvenation -- using laser illumination to extend the operational life of satellites that would otherwise cease to function due to array degradation in excess of 1-sun design margins (Landis, 1991a and Meulenberg, 1992). A longer term (5-6 years) demonstration is also described that involves using laser beamed power to illuminate a solar-electric propelled orbital transfer vehicle to minimize and compensate for array degradation occurring during transit through the Van Allen radiation belts. This paper examines laser facilities/equipment, target satellite, beam availability, and beam wavelength requirements that might be associated with such demonstrations, These considerations lead to:

- Identification of the U.S. Army's Oro Grande Laser 1 est Facility, Boeing's Free Electron Laser (FEL), and the Jet F'repulsion Laboratory's Beam Transmission Optical System (BTOS) as facilities and equipment vital to a satellite rejuvenation demonstration of laser-beamed power technology,
- Selection of NASA's TDRS-1 as a target satellite for the rejuvenation demonstration and identification of TDRS power subsystem performance characteristics indicative of experiment success, and
- Preliminary definition of 2 potential high-value technology demonstration experiments with laser-electric propulsion.

In the process of developing this plan, certain technical challenges have been addressed, including:

- Determination of probable TDRS-1 solar cell output response to beam wavelengths suited for atmospheric penetration and eye safety,
- Confirmation of the satellite rejuvenation concept's applicability to high altitude, low inclination satellites, and
- Estimation of beam interruption probabilities for non-targeted satellites.

The demonstration program outlined in this paper, if pursued, will represent the first practical demonstration of transmitting electrical energy through space using laser bearned power and presents an opportunity for the development of commercial applications for this new technology.

1.0 INTRODUCTION

The demonstration program proposed in this paper is intended to complement an active research and development program to advance and demonstrate capabilities in a number of technology areas including laser technology development, adaptive optics, atmospheric propagation, and photovoltaic material research. As such, it represents a proposed goal for laser beamed power technology development. The results of the demonstration program are specific products designed to demand specific advances from the technology program while also demonstrating the potential for near-term commercial and scientific applications. The demonstration program also attempts to minimize development costs by establishing synergistic working arrangements with other organizations. These organizations (both government and private industry) have been independently developing laser beam power system components for a variety of different programs and projects, l-he strategy of the demonstration program is to focus on the *integration* of these components. The demonstration program is proposed as two phases.

The first phase involves illuminating an existing satellite to validate the potential for satellite power rejuvenation. The loss of communications satellites due to power drainage during eclipse periods has been a key life-limiting design issue. 1 here is a projected economic value to the extension of communication satellite lifetime of 12 to 35 million dollars per satellite depending on the size of the ground systems (Meulenberg, 1992). This experiment will demonstrate the transmission of laser beamed power and verify effective power delivery at a specific beam wavelength for the purpose of maintaining battery storage during satellite eclipse.

The second phase would involve illumination of an electrically propelled spacecraft to augment solar electric propulsion. The Phase 2 activities will extend the Phase I requirements because of the higher transit velocities of the vehicle at lower altitudes relative to the ground station. Phase 2 will also identify atmospheric-dependent operational limits to tracking low altitude spacecraft and will build on subsystem integration by laying the groundwork for the architecture of an end-to-end operational system. Finally, the Phase 2 demonstration will provide a test of the value added benefits of laser beamed power to solar electric propulsion in terms of trip time and mass savings.

2.0 LASER FACILITIES AND EQUIPMENT

An attribute of laser beamed power technology is its inherent ability to provide stepwise increases in power delivery as it is scaled to larger aperture sizes. It is possible to construct the beam transmission structure and optical system early in the development phase using only a small fraction of total aperture area for the initial set of mirror segments. Hence, the technology lends itself to a phased demonstration program in which technical issues can be examined and tested in an evolutionary fashion during buildup to a full-scale system.

The proposed demonstration program would involve the integration of a 100-500 kW free electron laser (FEL) and a prototype beam transmission optical system. Such a laser is currently being developed under a cooperative agreement between the U.S. Army, Boeing Defense and Space Group and Los Alamos National Laboratory (Lamb, 1992). The system is scheduled for installation during 1994 at the Oro Grande Laser Test Facility at White Sands Missile Range (U.S. Army, 1987; Parazzoli, 1991).

The High Energy Laser Systems Test Facility located at the U.S. Army White Sands Missile Range is the National Tri-Service facility for the testing of high energy laser systems (White Sands Missile Range, 1991). The facility is managed by the U.S. Army Strategic Defense Command and supports U.S. Government, industry, and foreign government requirements for testing the effects of high energy lasers on a variety of target articles. The centerpiece of the facility is a third generation Mid-Infrared Advanced Chemical Laser (MIRACL). This megawatt-class laser is the most powerful chemical laser in the free world and operates at a wavelength of 3.8 microns.

in addition to a variety of test chambers, work is underway to build a 100 kW average power free electron laser with a goal of demonstrating a fully operational, radio-frequency pulsed system at 1.06 microns wavelength. The current laser design uses four 4 MW peak-power (1 MW average-power) klystrons to power the accelerator and is designed to operate al a frequency of 1.06 microns (Parazolli, et al., "1991). With modifications, it would be possible to tune the wavelength to nearby regions of the spectrum for experimental analysis of wavelength effects on power transmission and conversion (Lamb, 1992). The proposed Phase 1 satellite rejuvenation experiment, subject to deriving the necessary institutional agreements, proposes to use this planned FEL to illuminate the satellite selected for the demonstration,

The beam transmission optical system (BTOS) used to track and focus the beam on the satellite is shown in Figure 1, Currently under development through an agreement between the Marshall Space Flight Center and the Jet Propulsion Laboratory (JPL, 1992), tracking an object at geosynchronous orbit (GEO) would be well within the Phase I system requirements. Whether an aggressive program could deploy such a system within the two year Phase I period would depend on funding resources. However, should insufficient funding preclude an early demonstration of the segmented mirror approach, an alternative exists in the Navy's SEALITE beam director presently co-located with the MIRACL system at White Sands. While the SEALITE system represents a different technological approach without the technology growth advantages of the segmented system, it currently exists, is operational, and is capable of tracking and illuminating objects traveling at speeds greater than Mach 2-- well beyond the Phase I satellite rejuvenation requirements for tracking an object in Geosynchronous orbit.

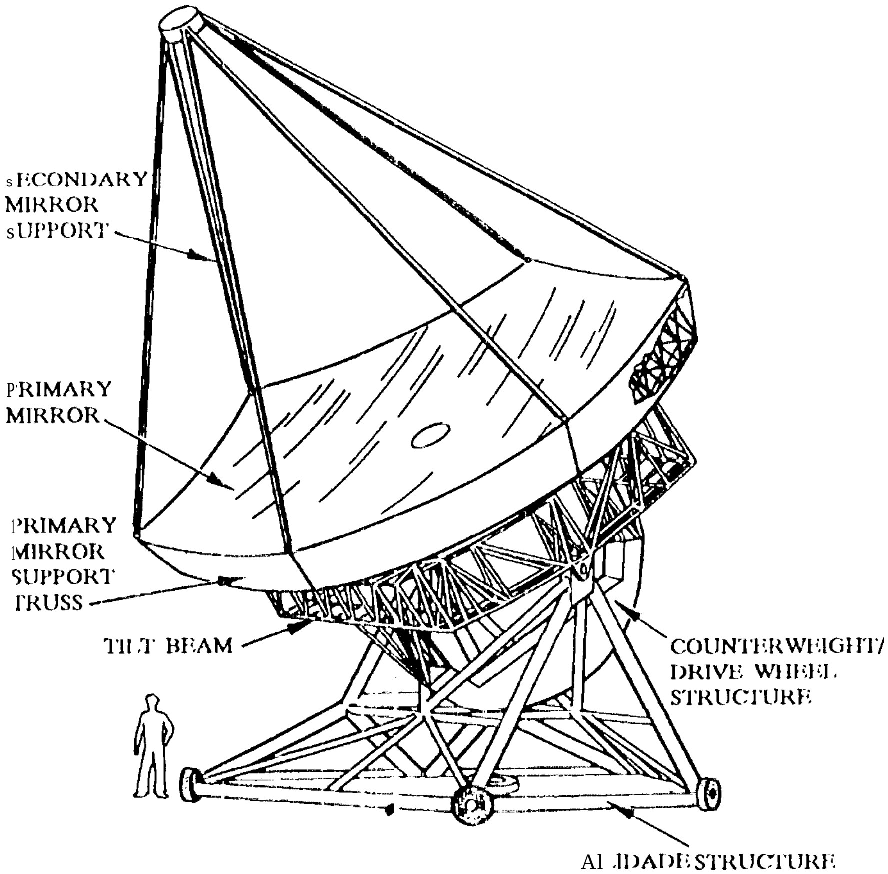


Figure 1, Beam Transmission Optical System

3.0 PHASE I DEMONSTRATION: SATELLITE REJUVENATION EXPERIMENT

Satellite lifetimes not constrained by their supplies of consumable fluids and/or gasses are (in the absence of malfunctions) ultimately constrained by the lifetimes of their solar arrays and batteries, Solar arrays tend to degrade in the presence of high-energy electrons and protons. When the arrays degrade to the point of no longer being able to supply the full baseload power requirement, the batteries begin discharging to compensate. Since the batteries are required for off-sun periods, this discharge eventually drains them and the satellite fails for lack of power.

Earth-orbiting satellites are particularly vulnerable to array degradation due to the Van Allen radiation belts (Angrist, 1982), These doughnut-shaped belts reach maximum intensity at approximately 4,600 km and 20,000 km. According to Angrist, the inner belt has an electron flux of about 10 million particles per square centimeter at energies beyond 1 MeV (sufficient to significantly degrade an unshielded scalar cell in 3 months) and a proton flux of about 300 million particles per square centimeter at energies of 0.5 MeV to 1 MeV (sufficient to significantly degrade an unshielded solar cell in 30 hours). The outer belt particles, while more widely distributed, have energies significantly higher. For instance, the omnidirectional proton flux is about 1 0,000 particles per square centimeter at energies in excess of 30 MeV.

While satellite solar arrays are generally shielded to better withstand such radiation, array degradation is still a life-limiting consideration for satellite design. 1 he T racking and Data Relay Satellite (TDRS), for example, is designed to have a 3.1kW capacity at beginning of mission and 2,2 kW ten years later at end of mission -- a projected degradation of about 29% over 10 years (Angrist, , 1982).

Because array degradation limits the operational lifetime of satellites, the Phase I demonstration proposes to extend satellite operational lifetime by artificially increasing the solar intensity incident on the arrays for periods long enough to recharge the batteries. The planned FEL to be installed at White Sands can provide the means for demonstrating, with minimal financial outlay, near-term economic and scientific benefits to laser-beamed power by extracting additional utility out of existing satellites via an extension of their effective lifetimes. No multi-hundred million dollar spacecraft need be built and launched on a multi-hundred million dollar launch vehicle to achieve this demonstration. "The demonstration itself may significantly delay the need to build and launch equally expensive follow-on satellites to the satellite involved in the demonstration. These savings are likely to offset the operations costs associated with using the FEL.T bus, in the process of showing the technical practicality of laser beamed power, the demonstration could open a new commercial market centered around rejuvenating aging communications, meteorology, and remote sensing spacecraft.

3.1 Satellite Selection

Before negotiation and planning for use of the above facilities and equipment in a satellite rejuvenation experiment can occur, a suitable target satellite must be identified. A number of selection criteria were used for identifying the population of potential candidates. These criteria included:

- Age: Satellites more than 15 years old were deemed too likely to malfunction or too degraded to be worth rejuvenating.
- Affiliation: Foreign satellites and Department of Defense satellites were eliminated on the assumption that agreements for their use would be too difficult to secure (and as a result, too costly).
- Orbit: Satellites in orbits likely to decay within four years or outside the range of the Oro Grande Laser Test Facility were eliminated.

- o Consumables: Satellites lacking sufficient propellant for station keeping over the next four years were eliminated.

- o Susceptibility: Satellites potentially vulnerable to radiation in the 0.5 to 2.0 micron range were eliminated.

After reducing the potential population of satellite candidates with these criteria, a set of specific criteria was applied. These criteria included:

- o Control interface: Satellite's not under NASA's direct control were eliminated.

- o Rejuvenation Value: Satellite's which, if rejuvenated, would not provide additional capability or forestall the need for a new spare were eliminated.

While the search was not exhaustive, approximately 340 potential satellites (NASA, 1992) were investigated. NASA's Tracking and Data Relay Satellite # 1 (T DRS-1) was selected from this set as the candidate satellite.

1 DRS-1 was designed for a 10-year mission (with no single point failures) to assist in providing a link between U.S. based ground stations, NASA earth orbiting spacecraft, and a domestic communications link for Western Union (Martin, 1991). The T DRS system link was accomplished by four spacecraft in geostationary orbit with two dedicated to NASA, one dedicated to Western Union, and the fourth is a common on-orbit spare. TDRS-1 was launched April 4, 1983. Almost 10 years old, the spacecraft is still capable of operation but at a point where solar array degradation is significant, It is , in geosynchronous storage orbit having an apogee of 35,804 km and a perigee of 35,776 km. Its orbital inclination is 2.3°. While its longitude is currently 170° (beyond the range of the Oro Grande Laser Test Facility), Goddard Space Flight Center (GSFC) is tentatively planning on moving the satellite to 107° west longitude for testing prior to moving it over the Indian Ocean to assist in data acquisition from the Gamma Ray Observatory (Liebricht, 1992). It still has a sufficient supply of consumables, and has no obvious sensitivities to radiation in the 0.5 to 2.0 micron wavelength -- although this insensitivity to laser illumination would have to be rigorously demonstrated before GSFC could consider allowing TDRS-1's participation in a satellite rejuvenation experiment.

While TDRS-1 was originally under SPACECOM's control, NASA now has full control of it and the other 1 DRS satellites. Unlike some other TDRS satellites, TDRS-1 is not under lease and while its utility has been reduced by component failures, it is still considered a spare for Pacific coverage and has the capability to add additional satellite communications relay capacity and forestall the need for a new spare.

3.2 TDRS-1 Power Subsystem Characteristics

The mass of each three-axis-stabilized TDRS satellite is greater than 2000 kg and has a tip-to-tip solar array span of over 17 m. The satellite power demand ranges from 1700 W (maximum) on sun to an average orbital eclipse demand of 1400 W (Clopton and Crum, 1978).

The single axis tracking dual wing solar array consists of 6 (3.84 x 1.28 m) deployable panels with aluminum honeycomb substrate and Kapton facesheets that are structurally supported by box beams made of graphite fiber reinforced plastic. Each cell in the array is a Spectrolab Silicon (Si) 10 ohm-cm chemically polished Ta_2O_5 antireflective coated hybrid aluminum back surface reflector (BSR) 20x40x 0,20 mm with a 0.15 mm thick uncoated ceria doped borosilicate glass cover. With an area of 29,5 sq. m. and a mass of 86,1 kg, the array delivers 3.1 kw at the beginning of mission and 2.2 kw at end of mission. The array is electrically divided into load carrying and battery charging sections. Its low mass substrate results in a low thermal capacitance which means that as little as 3 W

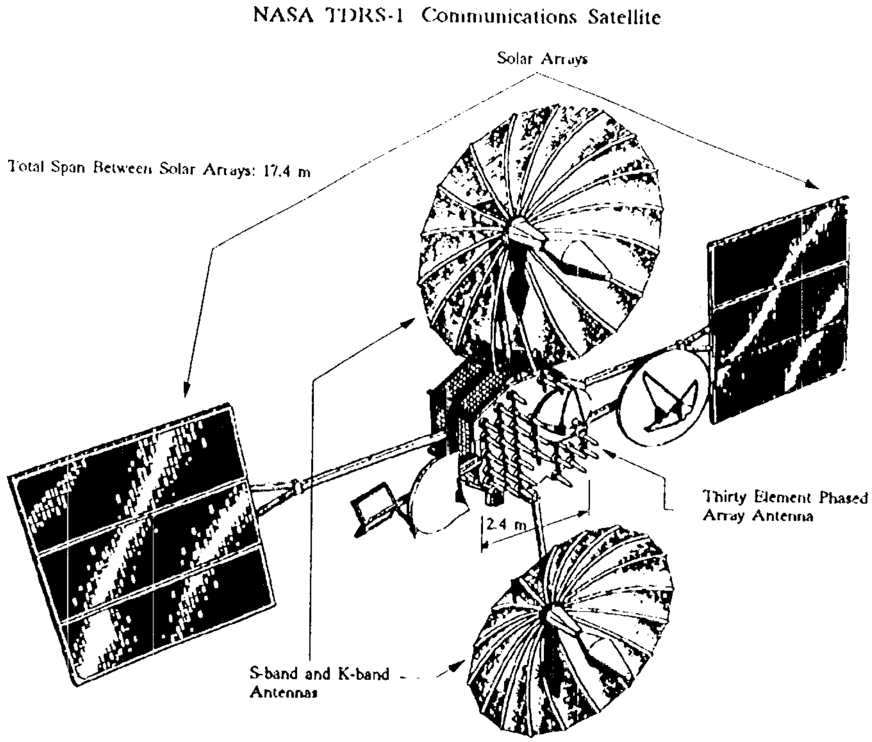


Figure 2. TDRS-1 Satellite (Martin, 1991)

of power dissipation in a cell for 2 minutes would melt the solder. However, a corrective design was implemented to prevent such hot spots. Groups of 10 cells in the charging section were shunted with bypass diodes to prevent reverse voltages greater than 10 V and dissipation greater than 2.7 W (Kelly and Kurkland, 1978; Raushenbach, et al., 1978).

Three Ni-Cd batteries (packaged in two boxes as three, half size batteries in each box) supply energy to the spacecraft during eclipse periods (1440 W for 1.2 hrs) with a nominal depth-of-discharge of 50% which could reach 75% with one battery failed, Each battery consists of 24 series connected 40-Ah sealed cells. The 10 year orbital life of the batteries is achieved by maintaining a temperature between O-5 “C (using redundant heaters and second surface mirror radiators) and proper charge management from the ground. On-board protection insures proper battery charging if a ground station outage were to occur and a solar cell current limit provides maximum battery charge current protection. Battery reconditioning capabilities in the power system are initiated prior to each eclipse season. Battery performance is assessed using: voltage data from each cell sampled every 30 seconds, ampere-hour integration data from the ground station, and battery current, voltage and temperature data, Additional battery protection that could influence a power beaming experiment is invoked by automatic termination of high-rate battery charging if battery temperatures reach 27°C by automatically switching to trickle charge (Kipp, 1980).

When the solar array is at operating temperature and continuous solar illumination, the bus voltage is controlled between 22 to 40 volts. Voltage is maintained by the batteries during eclipse and is limited by the batteries during eclipse exit where the cold array would cause bus surges if the batteries were not kept connected during array warm up. Simulated extreme worst case on orbit charging profiles have demonstrated no detrimental effects on the batteries. This combination of on-board system protection, ground command control and extensive instrumentation of the power system (particularly the batteries) makes this system amenable to a nondestructive demonstration of power beaming in space.

3.3 Laser Beam Power to Electric Power Conversion

Providing power during satellite eclipse can be used as a means of charging batteries for a degraded array or keeping a satellite operational during an eclipse which has insufficient usable battery capacity to survive the eclipse. The maximum wavelength of a laser for this application would be approximately 950-1000 nm for Si cells (used by TDRS) or 850 nm for GaAs cells,

Photovoltaic cells can exhibit very high efficiencies for laser to electric energy conversion. Reasonable efficiencies for Si cells can be achieved down to about 800 nm since cell efficiency drops linearly with wavelength to approximately 500 nm. If photon energy is below the bandgap energy of the cell, the efficiency will be zero. The cutoff wavelength (microns) = 1.24/ bandgap (electron volts). Theoretically, Si cell efficiencies of 40% are possible (Iles, 1990).

It is assumed that if a pulsed laser is used, the frequency will be very high and the interval between pulses will be less than the minority carrier lifetime (-1 O-100 microseconds for Si cells) causing the array to 'average' the power input and filter the pulse into a wave form. Although there are a number of technical issues related to the steady slate and transient response of photovoltaic material to these high-energy pulses, recent studies have begun to examine these issues (Anspaugh, et al., 1992; SELE NE, 1992). It is further assumed that the laser wavelength will be tuned to obtain the maximum efficiency possible from the solar arrays without violating any safety restrictions. When optimizing the performance of the array, cell temperature must also be considered because the efficiency is related to the operating temperature of the cell, particularly for Si cells, anti, in general, the lower the temperature, the higher the efficiency (Landis, 1991 b).

The interface between the wavelength of the laser and the wavelength response of the receiving solar cell material raises a number of technical issues surrounding the choice of laser wavelength. The Phase 1 demonstration will involve solar panels at the end of their mission life that have been subjected to extensive radiation exposure. The degradation of the cell material will affect the response of the material to the incoming laser wavelength. The Phase 2 demonstration will involve solar panels at the beginning of their mission life. At issue is the selection of a laser wavelength that provides effective power to both new and degraded solar cells (in this case, silicon). The choice of wavelength requires an understanding of the effects of long-term radiation exposure on cell response. As an initial step in this direction, a series of experiments were conducted to quantify these effects on cells that are as analogous to those on TDRS-1 as possible. The experiments and results are described further in the Technical Issues section of this paper.

Another technical issue facing both Phase 1 and 2 is that of beam availability. There are periods when the beam will be interrupted. These interruptions may be due to birds or aircraft straying into the exclusion zone or satellites intercepting the beam during operations. The low altitude interruptions can be addressed with local radar. However, Earth-orbiting satellites pose a more complex problem. The issue facing the demonstration program is to determine the magnitude of these potential satellite interruptions, This issue is also examined in further detail in the Technical Issues section.

4.0 PHASE II DEMONSTRATION: SUPPLEMENTING SOLAR ELECTRIC PROPULSION WITH LASER-BEAMED POWER

The aim of the Phase II demonstration is to extend the operational envelope of the Phase I system by (1) increasing the number of mirror segments, (2) increasing the output FEL power, and (3) enhancing the controllability of the ground system. As in Phase 1, the goal is to produce an affordable demonstration with useful results.

1 he concepts of laser electric and solar electric propulsion have been examined with increasing interest during recent years in both the propulsion and laser beamed power communities. Coupling this interest with recent emphasis at JPL in low-cost, higher risk spacecraft missions led to the pursuit of a concept with three complementary objectives: (1) the demonstration of laser beamed power for active propulsion of a spacecraft; (2) the demonstration of electric propulsion technology in an applied operational setting; and (3) the provision of active power to a scientific payload designed to measure the effects of radiation damage on photovoltaic materials as a precursor to Mars logistics payloads that will be exposed to high levels of radiation during transit through the Van Allen belt to their destinations.

Van Allen Belt Radiation Degradation. 1 he geomagnetic dipole field is responsible for the radiation belts near the Earth, holding the trapped charged particles for long periods of time. Particles trapped in the field will spiral about a field line with varying pitch angle and curvature in the inhomogeneous field, They move northward (or southward) until the pitch angle increases to 90°, then they reverse direction and travel back along the field line into the other hemisphere (Tada, et al., 1982). This latitudinal motion combined with a longitudinal drift in the motion of the charged particles causes" the radiation flux at any given point to be nearly omnidirectional. The electrons and protons trapped in this field can be quite energetic; electrons can have energies as high as 7 MeV and protons can have energies as high as 500 MeV. These energies are sufficiently high that they can produce a substantial amount of radiation damage to even a well shielded spacecraft orbiting within the belts.

T he space around the earth is not uniformly filled with these spiraling trapped particles. The radiation is most intense at the equator, and diminishes in the poleward direction at constant altitude, Also if a spacecraft remains at a constant inclination and increases in altitude, it would see an increase in the electron flux up to a maximum at an altitude of about 4,600 km. As the altitude increases further, the electron flux falls off, then again increases to another maximum at an altitude of about 20,000 km. These peaks occur in the regions known as the inner and outer trapped electron zones.

A similar observation is made for trapped protons. There is one rather ill-defined peak, occurring at altitudes between about 4,000 and 10,000 km, The 10,000 km peak was found by observing the effect the protons produced in a lightly shielded solar cell (25 μm of coverglass), which excludes protons with energies lower than 1.3 MeV. If the peak is defined using a cell with a slightly thicker shield (1 50 pm), which excludes energies below 4.0 MeV, the peak would occur at about 6,500 km, and so on. As far as the effect on solar panels is concerned, the damage induced at the peak of the proton belt is far greater than the damage induced in either of the electron belt zones. As an example, a TDRS-1 type solar cell shielded by 150 pm-thick coverglasses, orbiting at 6,500 km, would lose 50% of its power after Only about 34 days. A similar panel, orbiting in the outer electron belt at 20,000 km, would lose 50% of its power after it had been there for approximately 94 years. Thus it is clear that a spacecraft designed to slowly increase its altitude by means of a low thrust engine will encounter a harsh environment in certain portions of the journey.

A generic concept for such a spacecraft is illustrated in Figure 3. The spacecraft characterized here is designed to emphasize both the scientific and technology aspects of laser beamed power, To minimize development costs, the design consisted of a hexagonal 'can" covered on all sides by Silicon solar cells for receipt of ambient solar radiation augmented by high-energy laser transmitted power. The payload of the spacecraft was to be located at one end of the spacecraft in a manner similar to an earlier experiment performed by one of the authors (Anspaugh, 1972). Unlike the

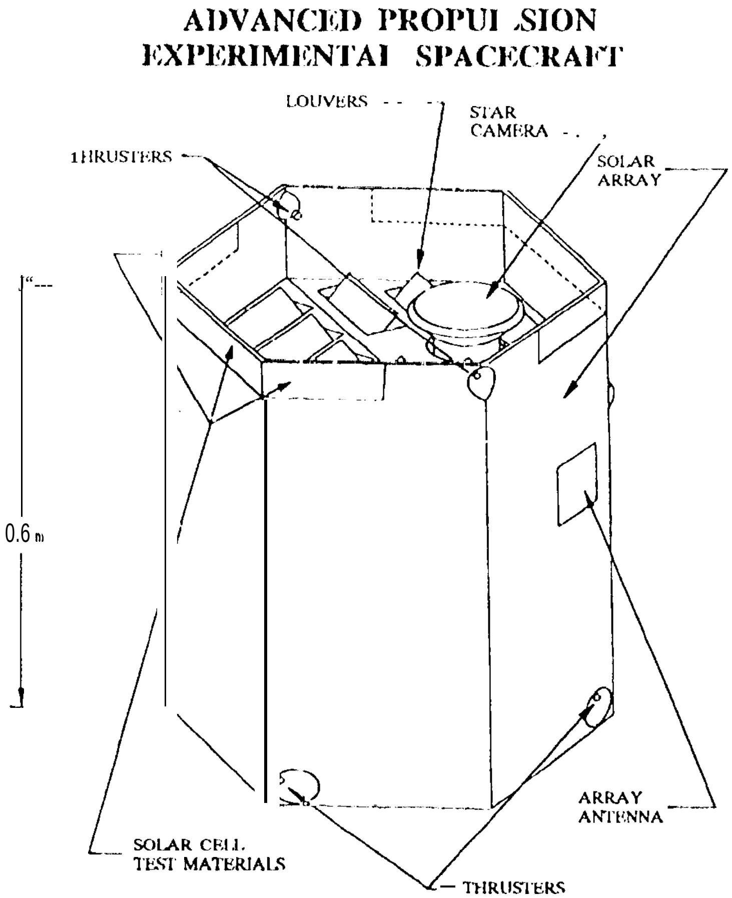


Figure 3. Generic Concept for A Laser/Electric Propulsion Experiment

more recent Photovoltaic Array Space Power Plus Diagnostics flight experiment (Cooley, et. al., 1992), the objective of this generic concept was to expose the test materials to the harsh environment of Van Allen belt radiation. While this concept would yield a variety of scientific, engineering, and technology benefits, questions still need to be resolved about total mass, whether the receiver configuration is sufficient without a deployable system, and the efficacy of spiraling outward to GEO versus inward from GEO.

An alternative, lower cost option was also examined that would eliminate the science payload and place an emphasis on technology demonstration, A cost savings in payload and spacecraft development could be achieved through development of an agreement with the Electric Insertion Transfer Experiment (ELITE) program (Robertson, 1991; Rosenthal, 1992). Because the Van Allen Belts will subject an orbital transfer vehicle utilizing low thrust, solar electric propulsion, to damaging levels of radiation, supplemental laser illumination of the orbital transfer vehicle's arrays could reduce such damage by providing higher thrust through the danger zones--thereby reducing the exposure duration. To the extent that radiation damage does occur, laser illumination can be used to offset array degradation--thereby prolonging the orbital transfer vehicle's utility, The ELITE spacecraft (Figure 4) currently being developed by the U.S. Air Force and TRW Corporation would offer an opportunity to test these hypotheses.

ELITE is to be launched on a modified Titan IIG vehicle and is intended to demonstrate 'independent operation' of an orbital transfer vehicle in the harsh environment of the Van Allen belts. The operational vehicle is designed to reach geosynchronous orbit from low Earth orbit within 180 days. During this time, the spacecraft's electronic components would be exposed to this high-energy radiation and the performance of standard solar panels could degrade by as much as 60% due to radiation damage (Robertson, 1991). As a subscale demonstration, ELITE is a precursor to larger

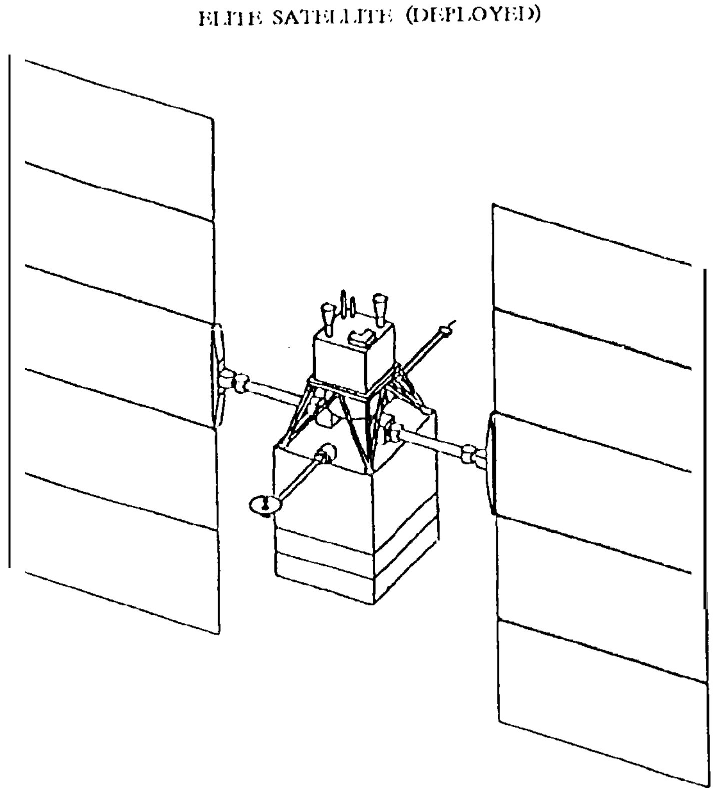


Figure 4. ELITE Concept (Rosenthal, 1992)

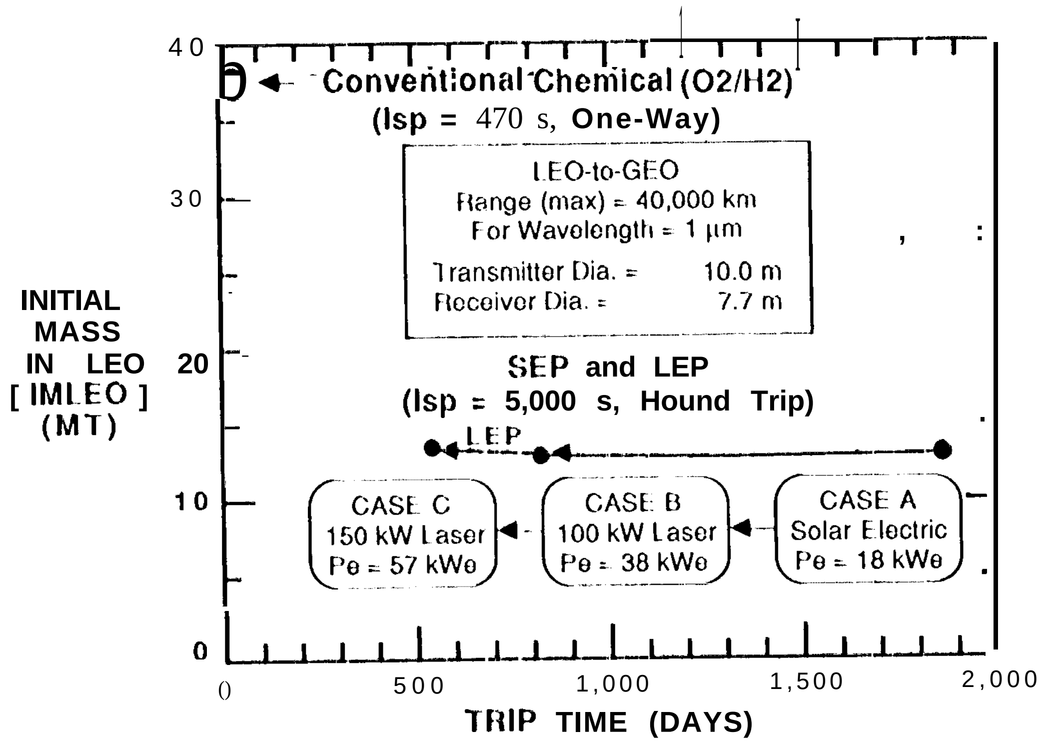


Figure 5. Comparison of Propulsion Option Trip Times for 10 Mt payload and 7'3% Atmospheric Transmission

vehicles capable of larger payloads, Figure 5 summarizes an analysis of solar electric, laser electric, and conventional propulsion for a 10 Mt class payload and illustrates how the tradeoff between a solar electric propulsion (SEP) system with a laser at 100 or 150 kW can reduce spacecraft trip time dramatically. An analysis of three cases was performed to examine this tradeoff. The figure clearly shows how trip time scales back with increased electric power input. Case A uses ambient solar alone and takes 1850 days 10 travel from LEO to GEO with an available electric power of 18 kW_e. Case B assumes the arrays are continuously illuminated with laser beamed energy from a 100 kW laser on Earth resulting in a trip time reduction of 1000 days. Case C shows that a 50% increase in ground-based laser power (to 150 kW) reduces trip time by an additional 63%, This nonlinear increase in performance (reduced trip times) illustrates the multiplicative effect of providing on-board power from the ground.

Augmenting ELITE with laser-beamed power in a second demonstration phase would extend the lessons learned in the first phase by testing laser beamed power tracking, wavefront compensation, and transmission to a moving payload. The rationale for supplementing solar electric propulsion with laser beamed power would be strengthened by direct evidence of the benefits obtained from the Phase II demonstration experiment.

However, the Phase I and Phase II concepts raise a number of technical issues that need to be examined before more detailed planning can occur. A preliminary assessment of some of these issues is presented in the next Section.

5.0 TECHNICAL ISSUES

5.1 Beam Availability

Laser-beamed power's viability, whether it is applied to satellite rejuvenation, orbital transfer vehicle propulsion, or lunar power, depends to a great extent on the number of interruptions anticipated in the beam-target link. These interruptions arise from three sources: blackout periods occurring naturally from the target's orbit relative to the Earth's, beam shutoffs due to beam interception by non-target objects, and down-time due to scheduled and unscheduled maintenance (e.g., failure outages). Because reliability issues c:an be addressed by design factors, the focus of beam availability in this paper was on blackout and beam shutoff periods.

Blackout Periods Arising Naturally from the Target's Orbit Relative to the Earth's. Unless the target satellite is in geosynchronous orbit, its orbital period will be greater than the Earth's rotational period. As a result, the target satellite will not always be within range of the laser-beamed power facility. The amount of time it is in range depends on its altitude. As shown in Figure 6, the average visibility duration at high altitudes is greater than that at low altitudes. Below 1000 km the visibility duration ceases to be useful for laser-beamed power applications. Hence, satellite rejuvenation and more advanced laser-beamed power concepts such as laser electric propulsion are not feasible for low earth orbit (LEO) applications, Note, also, that a target satellite in higher inclination orbit will be in sight of the beam for a duration less than its equatorial counterpart due to the added latitudinal component of motion, Note, also, that by combining the viewing duration curves of Figure 6 with the analysis of Figure 5, the trip times for each of the cases illustrated can be characterized as a function of altitude savings as in Figure 7. Thus, laser-augmented solar electric propulsion provides a 10% reduction in trip lime through one of the most intense regions of the Van Allen belts (e.g., 20,000 km)

Shutoff Due to Beam interception by Non-targeted Objects. Birds, aircraft, and satellites may periodically enter the beam exclusion zone causing beam interruption. For its White Sands facility, the U.S. Army has automatic laser safety procedures that it would implement to preclude laser illumination of birds and aircraft (US. Army, 1987). These procedures include the restriction of air space, limitation of beam inclination to 45° or more above the horizon, and use of a radar at the FEL site that would automatically abort operation of the laser beam should an object 1.0 cm in diameter or larger be detected within 1.0 km of the beam. Technically, beam shutoff would involve defocus of the beam

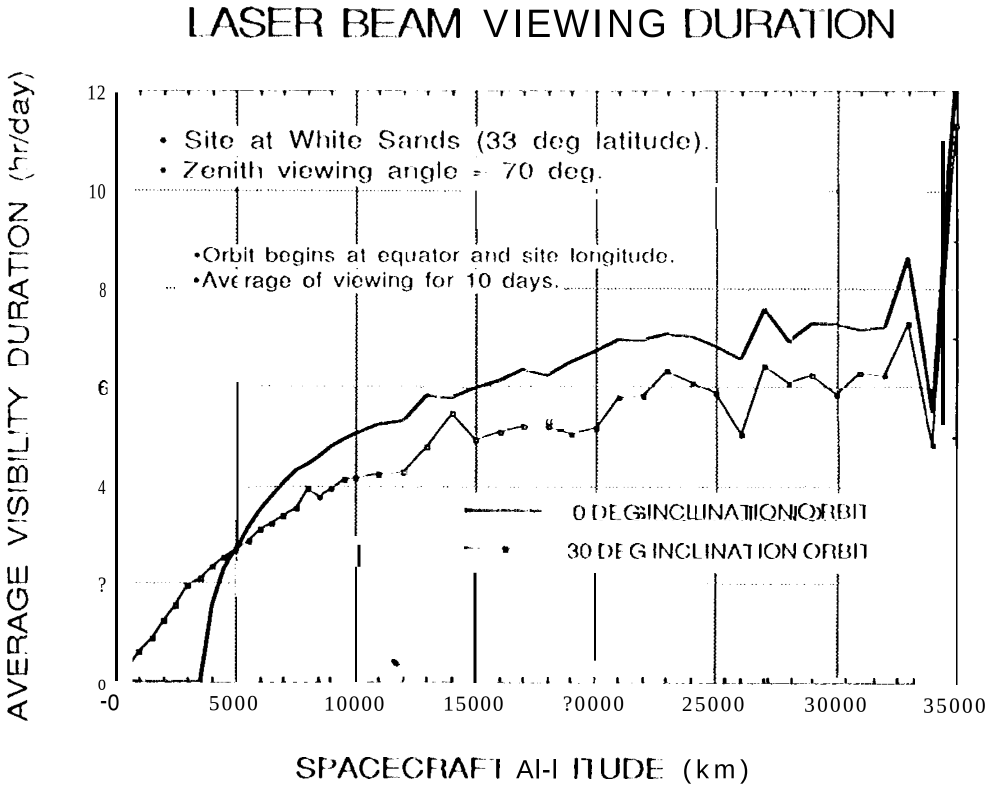
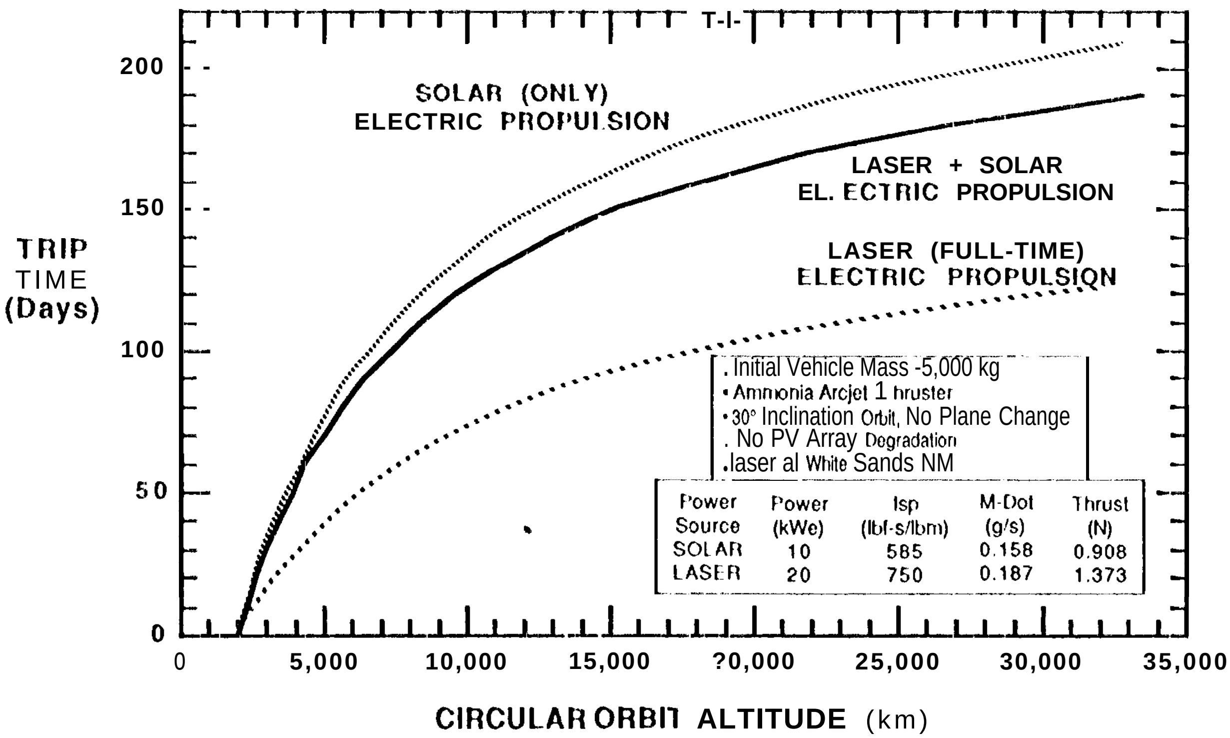


Figure 6. Laser Beam Viewing Duration



Power Source	Power (kWe)	Isp (lbf-s/lbm)	M-Dot (g/s)	Thrust (N)
SOLAR	10	585	0.158	0.908
LASER	20	750	0.187	1.373

Figure 7. Attitude versus Trip Time for Laser-Augmented Propulsion

MIRACL system at White Sands can be shut off within 7 milliseconds), Note that if the beam exclusion optics (depending on the length of the interruption) requiring less than 1 second (for example, the zone has a radius of r km, the lower limit on shutoff time can be approximated by r/v where v is the velocity of the object, Thus, if a bird travels at 0.01 km/s, an airplane travels at up to 0,5 km/s and a satellite travels at 10 km/s, the minimum required shutoff times are 100 seconds, 2 seconds, and 100 ms, respectively -- an achievable requirement,

For satellites, beam interception will generally be computed ahead of time and agreements would be necessary with the satellite owners as to whether the beam would be shut off or left functioning during interception. Some power interruption can be expected, To obtain an approximation of how frequently such interruptions might occur, a simplified satellite intercept model was developed that assumes the satellite target is in geosynchronous orbit (GEO), the intercepting satellites are in circular orbits, and that the intercepting satellites have inclinations greater than the beam location latitude (otherwise, no intersection occurs), Based on these assumptions, the model yields the number of times a satellite with a given altitude is likely to come within a 1 krn distance of the beam during a year,

Figure 8 illustrates these satellite interceptions as a function of orbital altitude, For all satellites below 2000 km, an average beam crossing probability of 0.4 is predicted for any given year. Hence, for 500 such satellites, the expected number of interceptions is about 200 per year or an average of 0.6 interruptions per day, For 3000 such satellites, the expected number of interceptions is about 1,200 per year or an average of about 3.3 interruptions per day, The cumulative number of interceptions pctr year for all altitudes up to GEO will be the crossing probability for each altitude times the number of satellites at that altitude summed over all of the altitudes. Note that at GEO, if the beam is aimed at one GEO satellite, interceptions with other GEO satellites will not occur. However, beyond GEO, the residual beam is once again subject to interception.

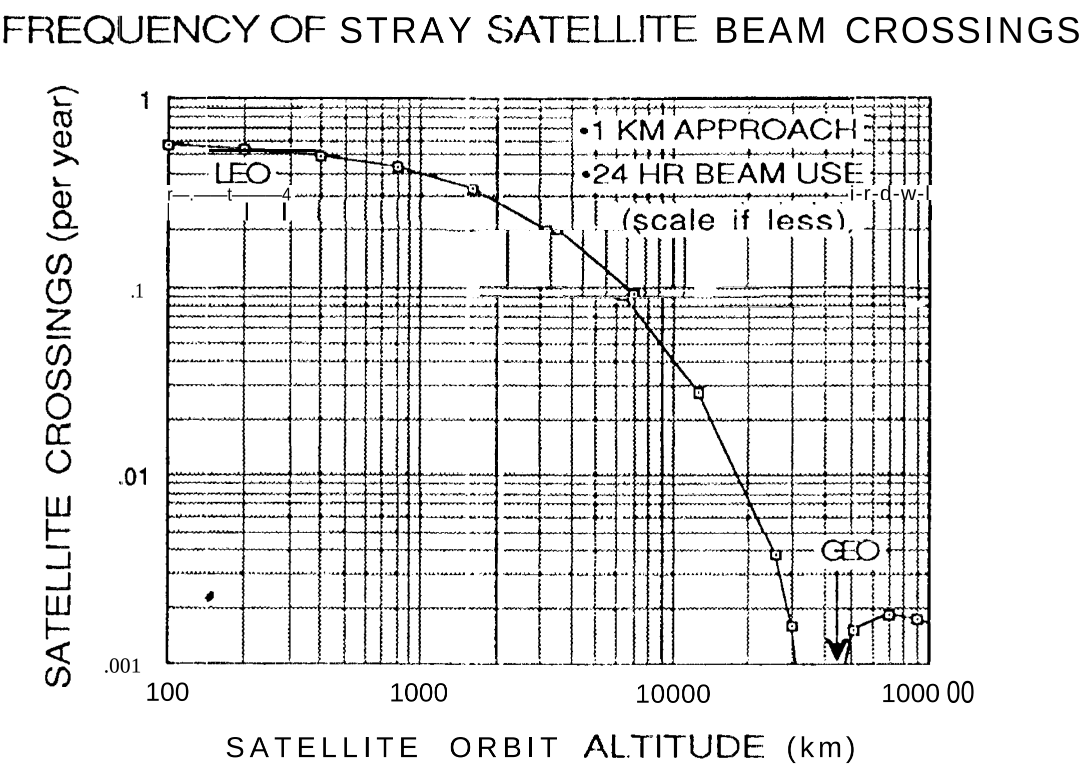


Figure 8. Frequency Distribution of Satellite Interceptions

The minimal effects of satellite interceptions on beam availability can be illustrated with a bounding example. If it is assumed the total shutoff time for a single interruption is 2-3 seconds, and a worst case value of 100 interceptions per day is assumed, the system availability would be reduced by only 3 to 5 minutes per day (out of a 4-6 hour duty cycle). 1 bus, it appears feasible to shut off the system for all satellite owners and preclude the necessity to develop individual agreements for maintaining constant operations. Furthermore, as shown in Figure 7, laser augmentation of solar electric propulsion by even a single ground station (e.g., White Sands) can provide significant reductions in trip times through the Van Allen belts.

5.2 Beam Wavelength Requirements

Unlike other laser-beamed power applications where photovoltaic materials designed for the beam wavelength can be postulated, the satellite rejuvenation experiment necessitates that the beam wavelength be adjusted to be compatible with the target satellite's existing solar arrays. At the same time, it is desirable to have the beam wavelength be compatible with atmospheric penetrability and eye safety requirements -- requirements that put the desired beam wavelength between 1 and 2 microns. Hence, solar cell output response as a function of frequency and degradation becomes a crucial matter for investigation.

5.2.1 Solar Cell Output Response as a Function of Frequency The basic structure of a solar cell is a large area n/p junction in a suitable semiconductor material. Contacts are added to the front and back of the cell, and certain other refinements, such as antireflection coatings, are added to enhance the efficiency of the cell. Light entering the cell produces charged particles internally, electrons and holes, Short wavelength, blue light produces charged particles very near the front surface of the cell, and long wavelength, infrared light produces charged particles deep within the cell. These particles created deep in the cell must travel long distances before they can cross the junction, which is near the front surface. These charged particles have very little chance of reaching the junction unless the semiconductor lattice is nearly perfect. Once they have crossed the junction, they can be delivered to an external load as electrical energy. If the lattice becomes damaged, fewer charges can reach the junction, and the deliverable output power is decreased.

One measure of a solar cell's ability to deliver power is its spectral response. This is usually measured by connecting an ammeter to the cell, (short circuit condition), and illuminating the cell with monochromatic light of known intensity. The spectral response is a plot of the cell's output current as a function of illuminating wavelength, and may be expressed in units of mA (output) per mW (input optical power), or in units of quantum efficiency, no, of electrons (output) / no. of photons incident.

The response of solar cells that are illuminated with monochromatic light is shown in Figure 9 (Iles, 1990), Figure 9 is a plot of this spectral response, expressed in units of conversion efficiency (electrical power output divided by optical power input), as a function of wavelength and semiconductor material. I-he materials with the highest output, Si and GaAs, have their highest response at wavelengths near 0.9 microns. CuInSe2 and GaSb have peak responses at longer wavelengths, but the present day efficiencies of cells made from these materials is quite low, and the cells are not available in production quantities.

5.2.2 Solar Cell Output Response as a Function of Degradation. In order for the long wavelength spectral response of a solar cell to be high, the lattice must be nearly defect free. This is typically how most new solar cells operate. However, after they have been subjected to radiation, such as that that found in the Earth's Van Allen belts, the lattices become distorted, the cells lose their red response, and tile output power of the cells decreases.

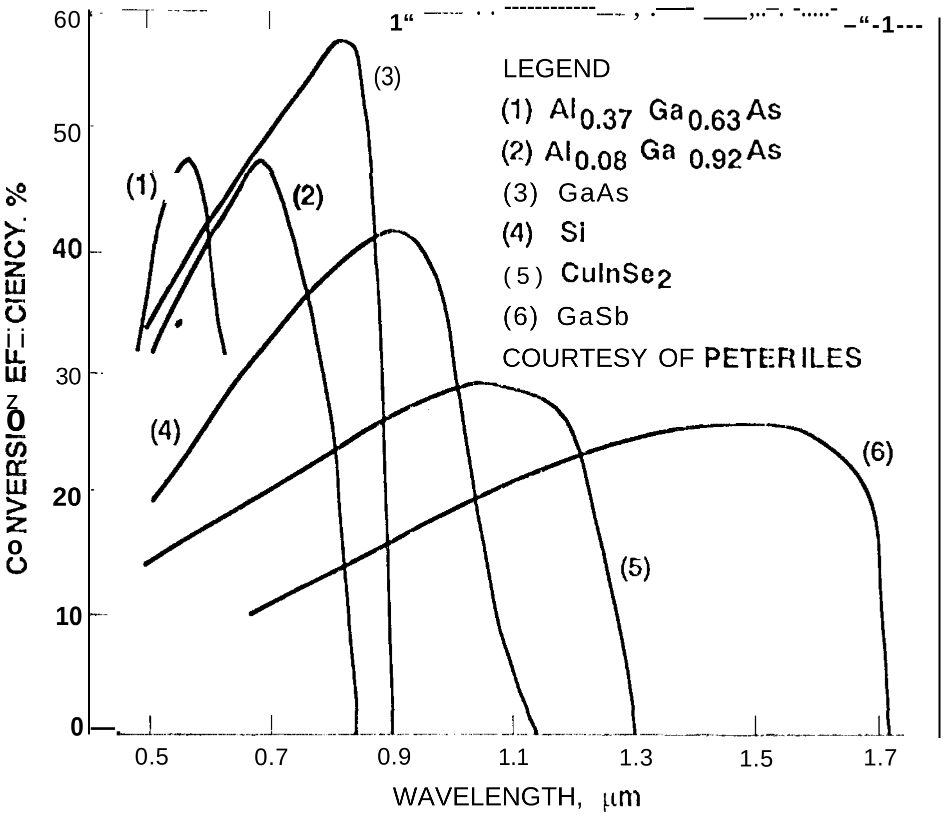


Figure 9. Cell Response

5.3 Solar Cell Degradation Experiment

An experiment was conducted to estimate the loss of spectral response for a TDRS-1 cell which has been in geosynchronous orbit for 9 years. Applied Solar Energy Corporation produces a solar cell that is very similar to those used on the solar panels of TDRS-1, It is 200 microns thick, measures 2 cm x 2 cm and has a two layer antireflection coating. The cell was irradiated with 2.3×10^{14} e/cm^2 of 1 MeV electrons -- equivalent to 9 years in geosynchronous orbit (not including solar flare protons).

The electron irradiations were performed at the JPL Dynamitron radialion facility illustrated in Figure 10a. An aluminum scattering foil, located 76 cm in front of the target plane, was used to spread the electron beam laterally so that the beam uniformity over the target piano exceeded ±5%. The cells were mounted to a temperature controlled block using small amounts of Apiezon H vacuum grease to maintain sample temperature within 28 ± 2°C during the irradiation. A small Faraday cup at the center of the target plane was used to monitor the flux and fluence.

Solar cell measurements mado before and after the irradiation included light current-voltage (I-V) curves and spectral response measurements. The I-V curves were measured using a Spectrolab X-25 Mark II solar simulator as the light source and a computer based data acquisition system as shown in Figure 10b. The simulator intensity was set using a standard solar cell which has been

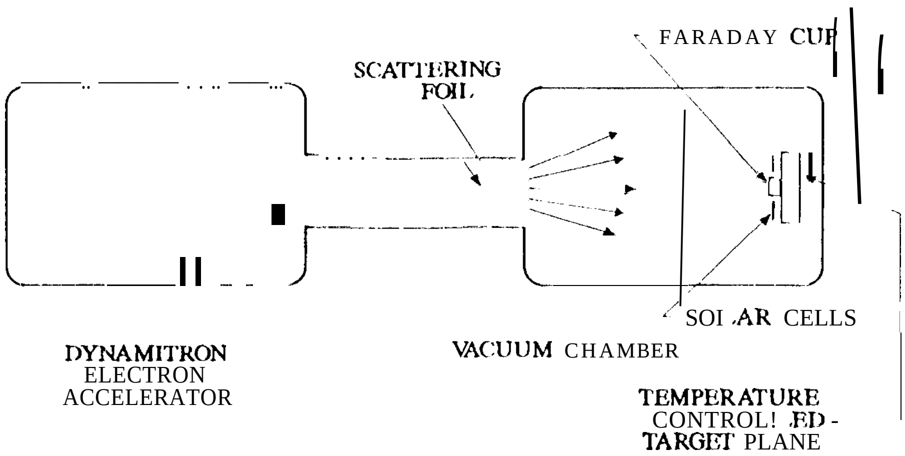


Figure 10a. JPL Dynamitron Radiation Facility

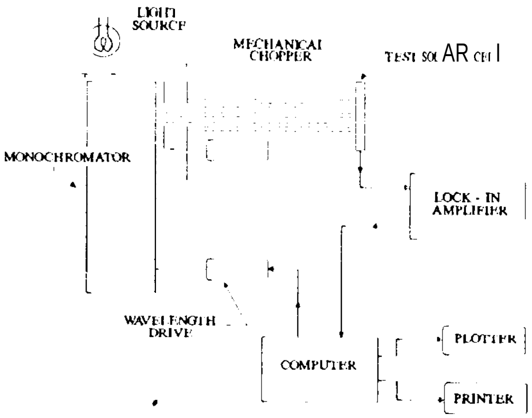


Figure 10b. Solar Cell Measurement System

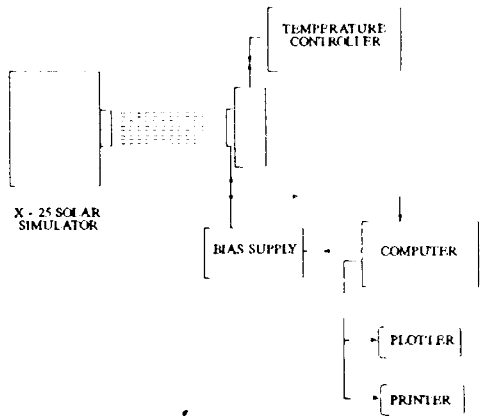


Figure 10c. Spectral Response Measurement System

calibrated on a high altitude balloon. The standard cell was chosen to have the same spectral characteristics as the cells under measurement,

The spectral response measurements were made with a calibrated system consisting of a light source and a monochromator, used to illuminate the solar cell under test with monochromatic chopped light (Figure 10c). The solar cell signal was coupled to a lock-in amplifier and a computer controlled data acquisition system to produce a plot of solar cell output versus wavelength.

Figure 1"1 illustrates the before and after spectral response curves from the TDRS-1 test cells. The loss in response was confined primarily to the infrared region. If the solar panels on the TDRS-1 were illuminated with the light from a laser operating at a wavelength of one micron, the curves show that the response of the cells would have fallen off to 70% of the pre-launch value. Their power loss over the full solar spectrum was only 13%, degrading from an efficiency Of 11 .7% to 10.2%. Hence, although it is desirable to operate an illuminating laser at the longest wavelengths possible for atmospheric and eye safety purposes, this is at odds with the requirement of a radiation damaged panel to operate at lower wavelengths.

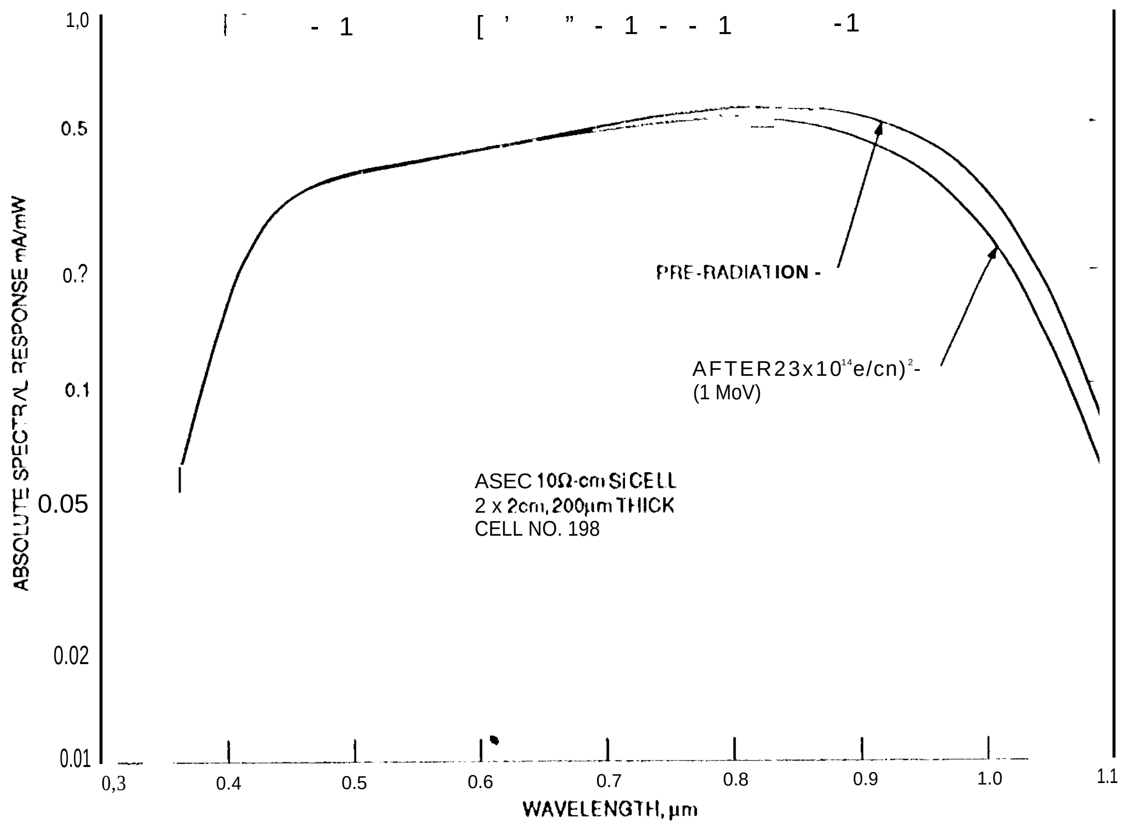


Figure 11, Spectral Response Degradation Results

6.0 DISCUSSION AND SUMMARY

In this paper, consideration has been given to what laser equipment and facilities, target satellite, beam availability, and beam wavelength requirements might be associated with a satellite rejuvenation demonstration. It has also been shown how this knowledge could progress to a second phase for the demonstration--laser illumination of a solar-electrically propelled orbital transfer vehicle to minimize and/or compensate for array degradation occurring during transit through the Van Allon radiation belts.

Laser equipment, facilities, and cost considerations render the U.S. Army's Oro Grande Laser Test Facility, Boeing's Free Electron Laser, and the Jet Propulsion Laboratory's Beam Transmission Optical System as a logical combination of capabilities for the phased demonstration of laser-beamed power technology.

in selecting a target satellite for this first phase, the criteria of age, affiliation, orbit, consumables status, radiation susceptibility, ownership, and utility were applied to eliminate most of the 340 candidate satellites examined. This 'filtration' process resulted in the selection of TDRS-1 as a target satellite. TDRS-1's condition, location, and active power subsystem lends itself to satellite rejuvenation and the condition of its solar arrays provide promise for experimental success.

The integration of components **for the Phase I demonstration will** help define the architecture for developing high-payoff applications in the propulsion arena. A low cost demonstration with scientific and technology benefits could be constructed with minimal development to show the benefits of laser-augmented solar electric propulsion in an applied scientific setting. Furthermore, if the necessary agreements were developed, use of the ELITE spacecraft could provide an even less expensive demonstration alternative.

However, the success of these experiments also depends on how long the beam-target link can be maintained without interruption. Analysis of the blackout period resulting from the difference between the target satellite's orbital period and the Earth's rotational period indicated that laser-beamed power is not feasible for satellites in low-Earth orbit. However, at high altitudes and low inclinations, such as those associated with TDRS-1, beam availability is high. For blackouts resulting from non-targeted satellite excursions through the beam, analysis indicated that such interruptions will, on average, occur approximately two times per day, These brief interruptions are not expected to significantly impact satellite rejuvenation or propulsion capabilities.

More important than the issue of beam availability is that of beam wavelength, Atmospheric penetrability and eye safety considerations render a beam wavelength of 1 to 2 microns desirable. However, the Si and GaAs solar cells typically used on satellite rejuvenation candidates experience diminishing efficiency at wavelengths of 1 micron and longer, Experiments conducted by the Jet Propulsion Laboratory's Dynamitron Facility on solar cells like those used aboard TDRS-1 indicated that this rapidly diminishing output at longer wavelengths is exacerbated by the degradation associated with TDRS-1's radiation environment and age. Only at wavelengths of about 0.67 microns or less does this degradation cease to influence laser-beamed power's effectiveness, Hence, further examination of the tradeoffs between atmospheric penetrability, eye safety, and rejuvenation duration (and/or beam intensity) will be needed before establishing a beam wavelength requirement for a TDRS-1 satellite rejuvenation experiment.

The demonstration experiments outlined in this paper are intended to stimulate discussion of how laser beamed power and its potential can be demonstrated. The experiments described herein are technically feasible within a cost-constrained budget environment owing to the use of existing facilities and minimization of new development costs. The underlying approach is to maximize the value of the R&D investment in a full scale system by purchasing (at low cost), the information and experience necessary to verify and assure that these concepts can be successful.

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